

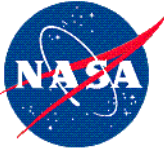


# High Input Voltage, Silicon Carbide Power Processing Unit Performance Demonstration

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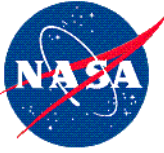
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AIAA Propulsion & Energy Conference, 27-29 July 2015  
Orlando, Florida



# Outline

- **Introduction**
- **Design Overview**
- **Design Specifications**
- **Test Setup**
- **Performance Results**
- **Forward Work**
- **Conclusion**
- **Acknowledgements**



# Introduction

- NASA's Space Technology Mission Directorate (STMD) Game Changing Development (GCD) Program was focused on developing a high-power, high-voltage Solar Electric Propulsion (SEP) system to revolutionize future missions requiring moving cargo and humans beyond low earth orbit.

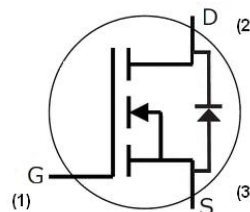
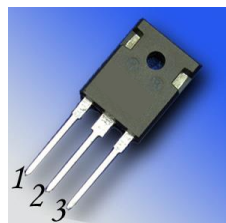


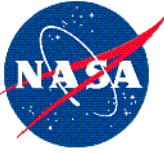
*A 300-kilowatt spacecraft concept for human exploration of Mars*



# Introduction

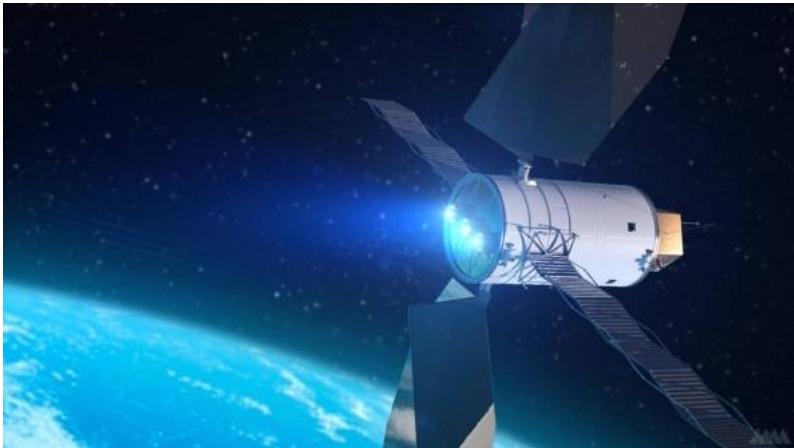
- In support of the STMD GCD, NASA Glenn Research Center (GRC) and the Jet Propulsion Laboratory (JPL) were tasked with demonstrating a high-power electric propulsion string.
  - Hall Effect Thruster Technology Demonstration Unit
  - High Input Voltage Brassboard Power Processing Unit (PPU)
- This presentation focuses on the design, integration, and demonstration of the brassboard PPU.
  - The brassboard PPU leverages previous design work of a breadboard discharge supply with Silicon Carbide (SiC) power switching devices.

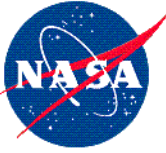




# Introduction

- Today, STMD is still developing and demonstrating innovative in-space propulsion technologies.
- A proposed SEP Technology Demonstration Mission would use technologies developed under the GCD program to support the design and flight of a SEP spacecraft.
  - 50-kW class SEP spacecraft
  - Electric propulsion for primary in-space propulsion

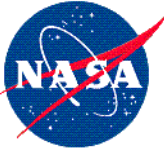




# Hall Effect Thruster









# Design Specifications

	<b>Maximum Output Power</b>	<b>Output Voltage Range</b>	<b>Output Current Range</b>	<b>Regulation Mode</b>	<b>Line/Load Regulation</b>	<b>Ripple</b>
<b>Discharge Supply</b>	15 kW	300-400 VDC	37.5-50 ADC	Voltage	$\leq 2\%$	$\leq 5\%$ peak- peak of regulated parameter
<b>Inner Magnet and Outer Magnet Supplies</b>	200 W	2-20 VDC	1-10 ADC	Current	$\leq 2\%$	$\leq 5\%$ peak- peak of regulated parameter
<b>Heater Supply</b>	324 W	6-36 VDC	3-9 ADC	Current	$\leq 2\%$	$\leq 5\%$ peak- peak of regulated parameter
<b>Keeper Supply</b>	90 W	10-30 VDC	1-3 ADC	Current	$\leq 2\%$	$\leq 5\%$ peak- peak of regulated parameter





# Power Supply Design

	Description	Topology	Control	Switching Frequency
<b>Discharge Supply</b>	Two 7.5 kW power supply modules with the outputs connected in parallel externally	Full-bridge converter with paralleled SiC MOSFETs and a single bridge rectifier with SiC Schottky diodes	PWM based on peak and average current control and an outer voltage control loop	30 kHz
<b>Auxiliary Supplies (Inner Electromagnet, Outer Electromagnet, Heater, and Keeper)</b>	Four separate power supplies; modular circuit board designs	Full-bridge converter with silicon MOSFETs	PWM based on peak and average current control	60 kHz



# Control and Filter Design

- **Master Control Board**

- Communication and control interface between the individual power supplies and the System Control Board (SCB)
- Receives analog and digital commands from the SCB and analog and digital telemetry from the power modules and input filters
- Generates PWM synchronization signals and the ignitor pulse command

- **System Control Board**

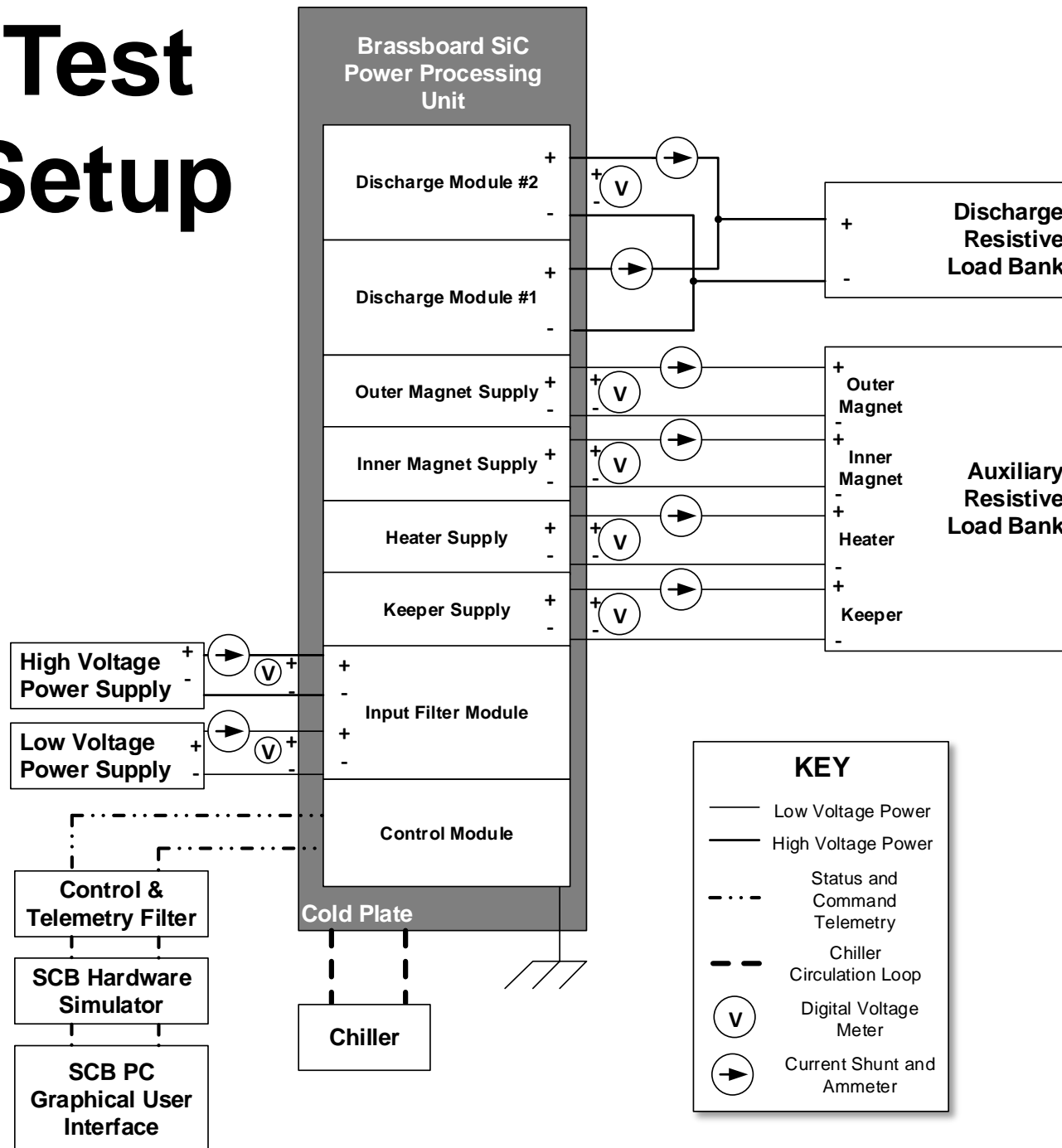
- Provides a control interface between the PPU, the thruster propellant feed system, and the flight system
- Currently under development at JPL

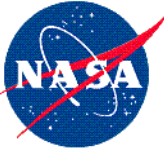
- **Input Filters**

- Separate filters for each input power bus
- Each filter consists of a differential low-pass stage and a common-mode inductor



# Test Setup



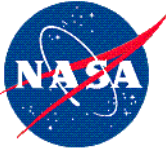


# Test Setup

- All of the instrumentation used for performance measurements during ambient testing was calibrated.
- Resistive load banks were used to simulate the thruster loads for both the ambient and vacuum testing.







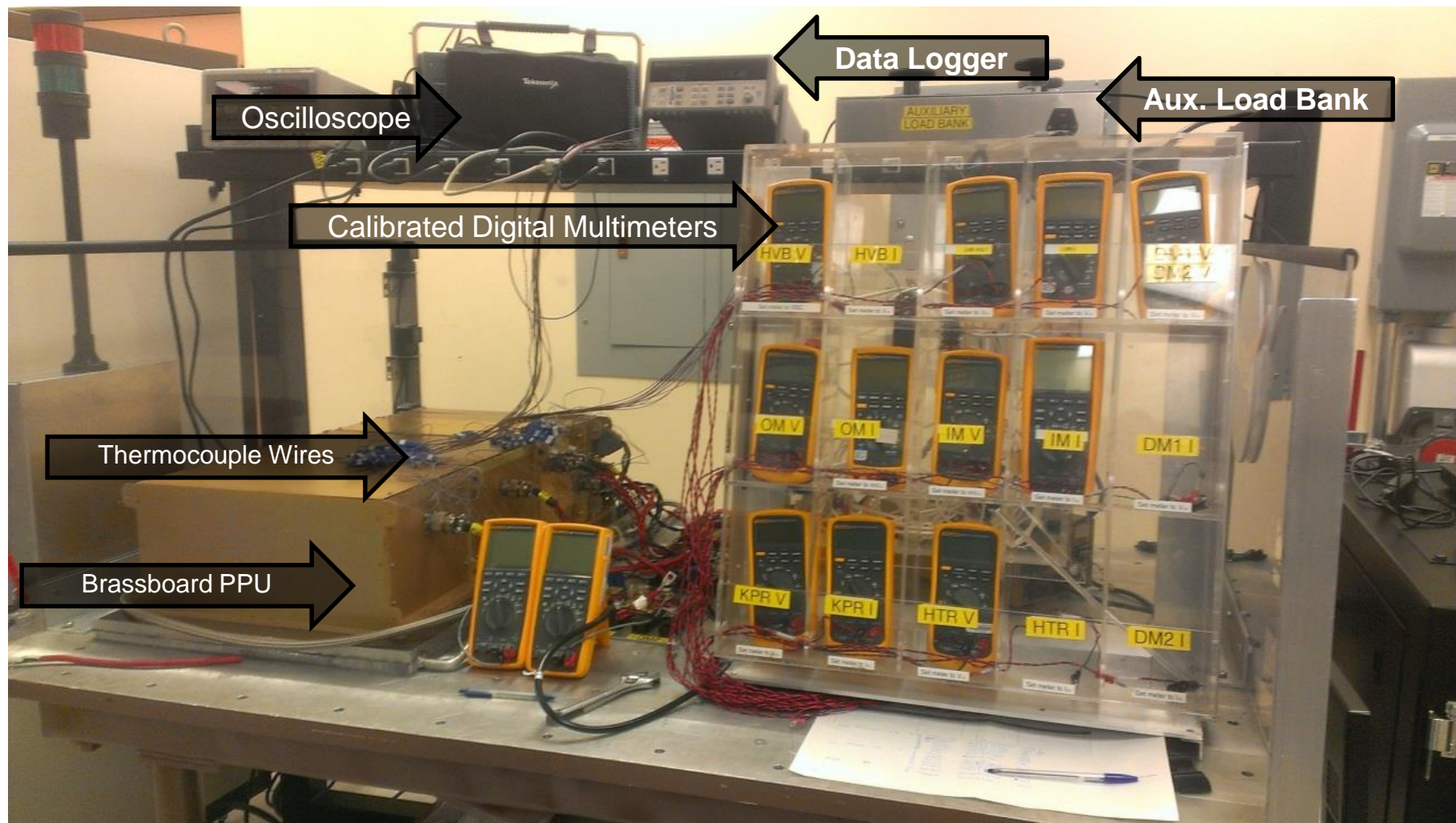
## Cold Plate

## Thermal Laptop

# Brassboard PPU



# Test Setup







# Test Setup

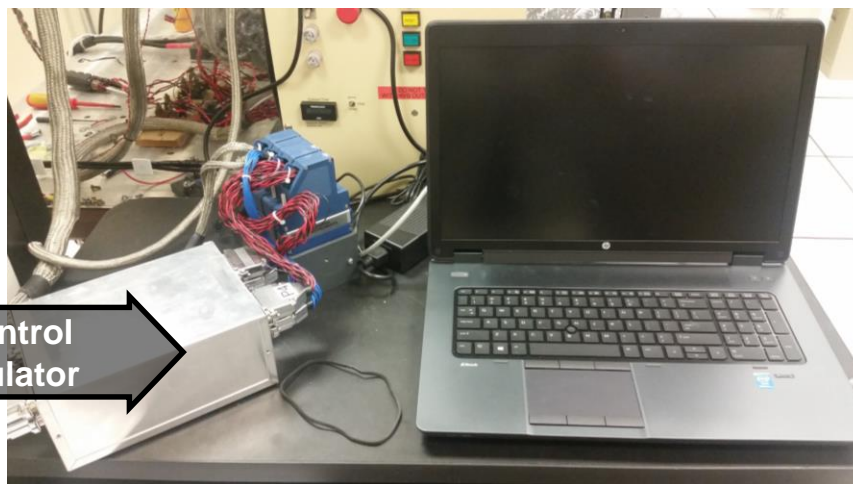


Discharge  
Load Bank

Power Supplies



System Control  
Board Simulator





# Test Setup

Host Main - V2.vi

File Edit Operate Tools Window Help

**Data Collection** → ReqData (green light) GetData (s) 1 Data Store Time (s) 2 Store Data (green light) Data File (\*.csv) [Browse]

**Flags** ← COMM Error [STOP] Calibrate

**Telemetry** ← **HVB and LVB**  
HVB Voltage 7.40 V OV UV  
HVB Current 0.02 A  
LVB Voltage 28.04 V OV UV  
LVB Current 0.34 A +15V 14.99

**Outer Magnet Supply**  
Voltage 0.04 V Current 0.24 A OC UC  
Outer Magnet Current SP 0.00 A Readback [F3]

**Inner Magnet Supply**  
Voltage 0.04 V Current 0.25 A OC UC  
Inner Magnet Current SP 0.00 A Readback [F4]

**Enable Switch** → Readback Voltage SP 50.00 V Current SP 10.00 A Imode [Reset] [Ctrl F9]

**Discharge Supply #1**  
Voltage 9.61 V Current 0.47 A OC  
Cathode Voltage -0.84 V OVn  
Chassis Fault [F1]

**Discharge Supply #2**  
Voltage 13.64 V Current 0.49 A OC  
Cathode Voltage -22.30 V OVn  
Chassis Fault [F2]

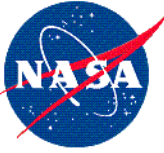
**Keeper Supply**  
Voltage 0.98 V Current 0.08 A OC UC  
Keeper Current SP 0.00 A Readback [F5]

**Heater Supply**  
Voltage 0.87 V Current 0.16 A OC UC  
Heater Current SP 0.00 A Readback [F6]

**Set Points** ←

Image of a satellite in space.





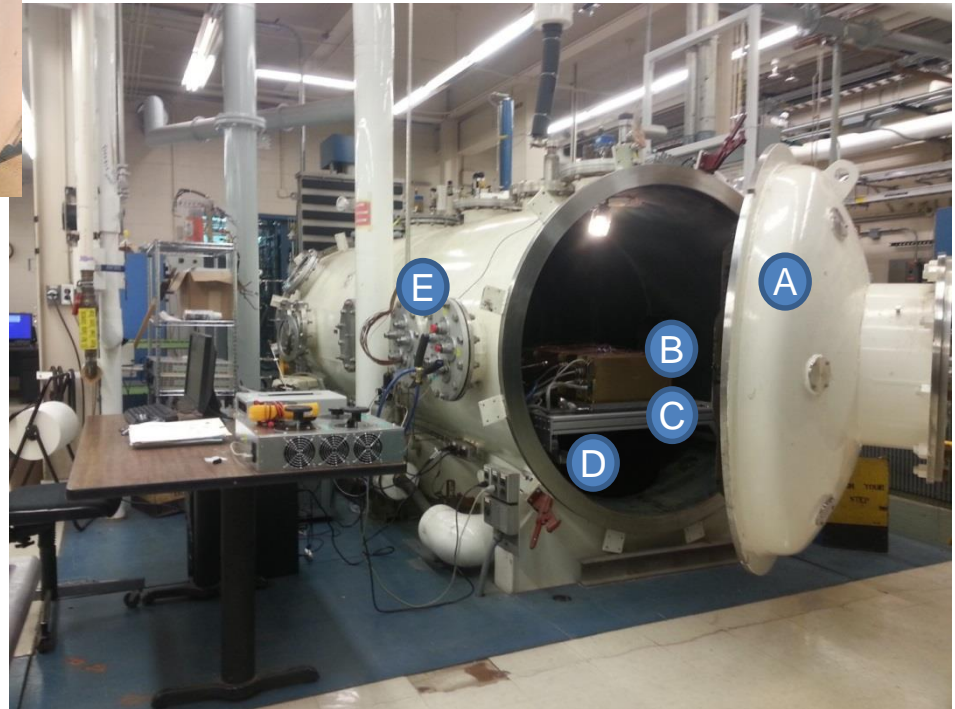
# Test Setup



## KEY

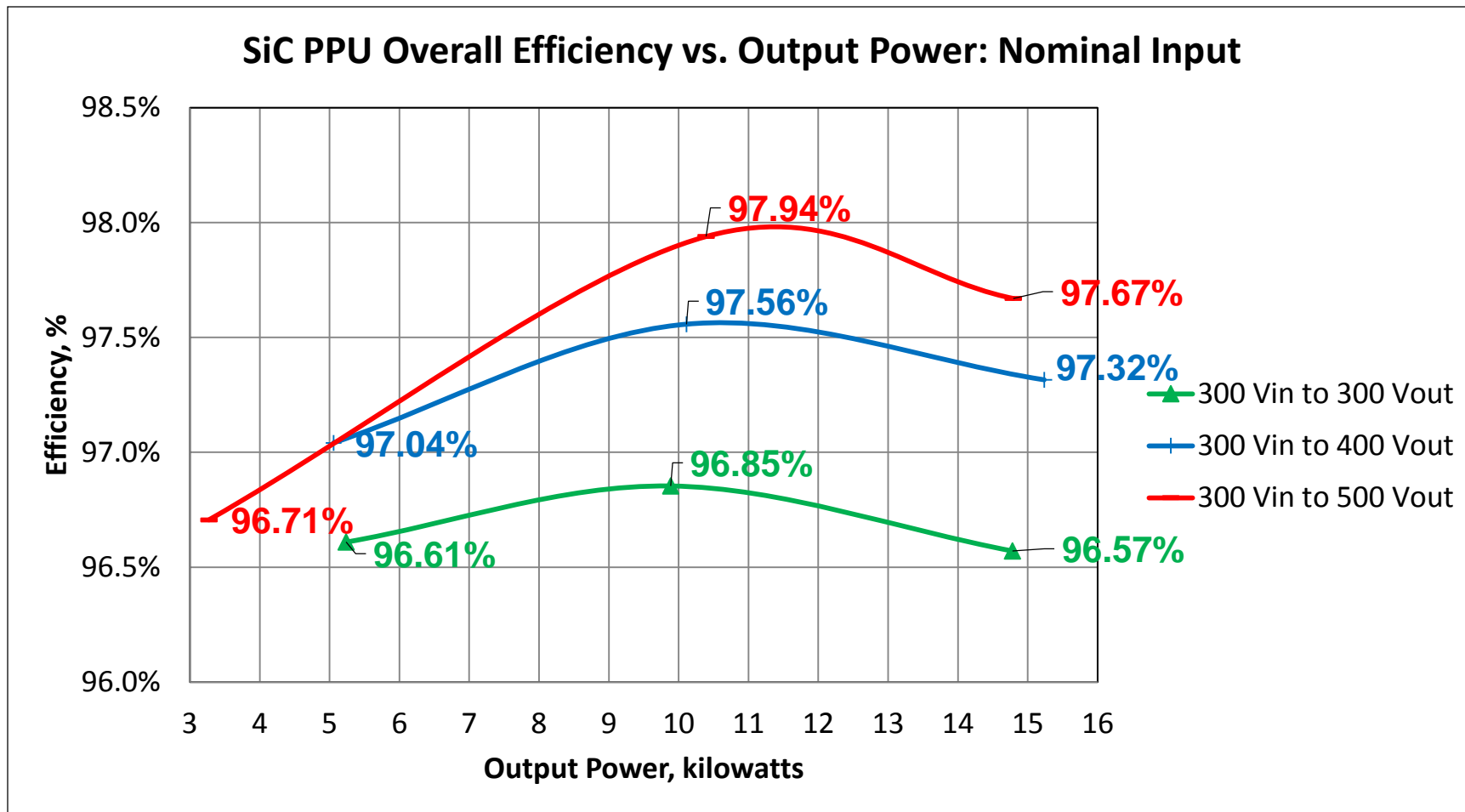
- A: GRC Vacuum Facility 8 (VF-8)
- B: HP-300V-PPU
- C: Cooling Plate
- D: Test Table
- E: Tank Feedthroughs

- Vacuum tank pressure was controlled by a separate facility control system to  $\leq 10^{-5}$  Torr





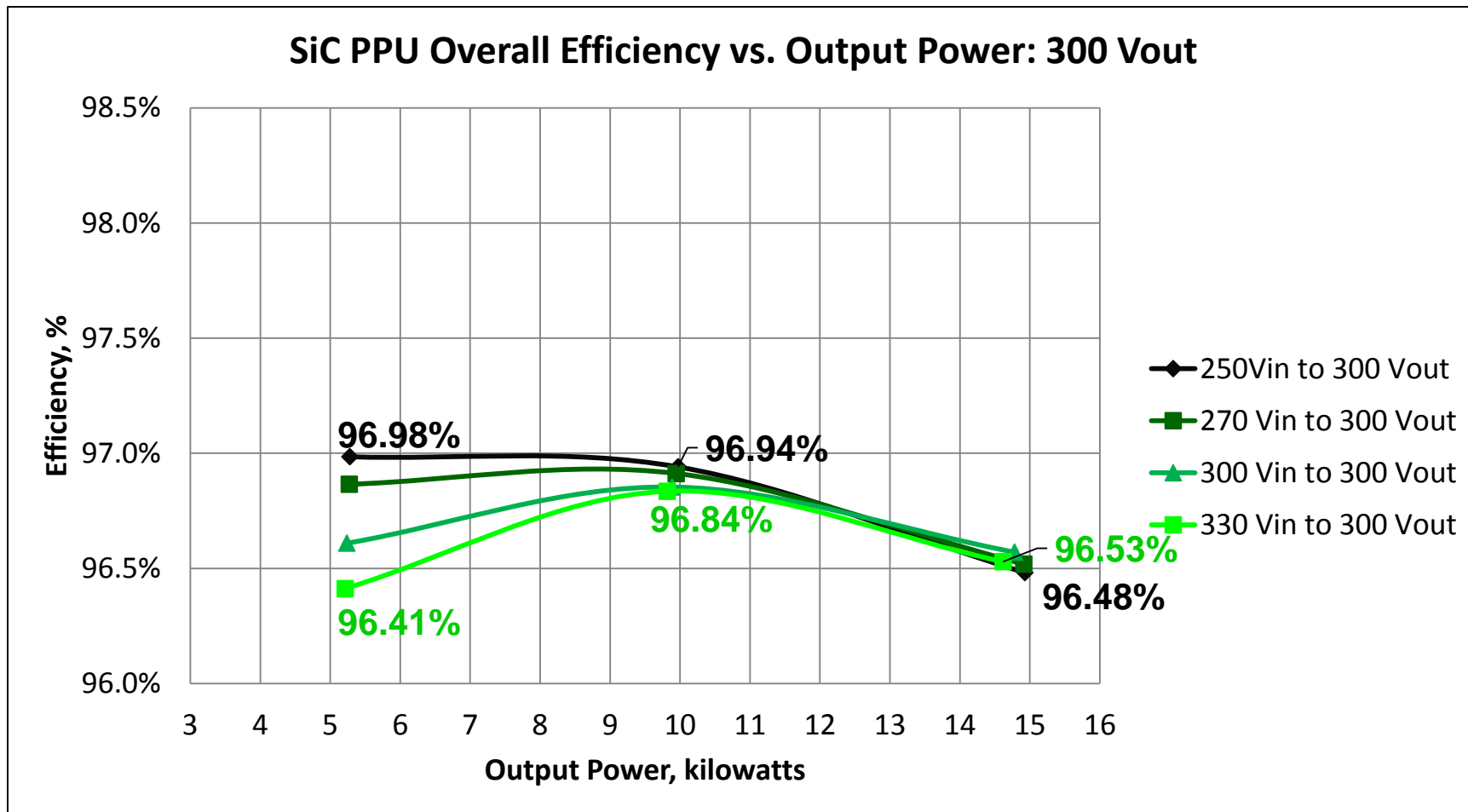
# Performance Results



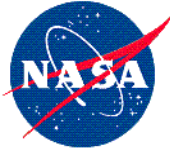
$$\text{Efficiency} = \frac{(\text{Discharge Output Power} + \sum \text{Auxiliary Output Power} + \text{Housekeeping Power})}{(\text{Low Voltage Power Input} + \text{High Voltage Power Input})}$$



# Performance Results

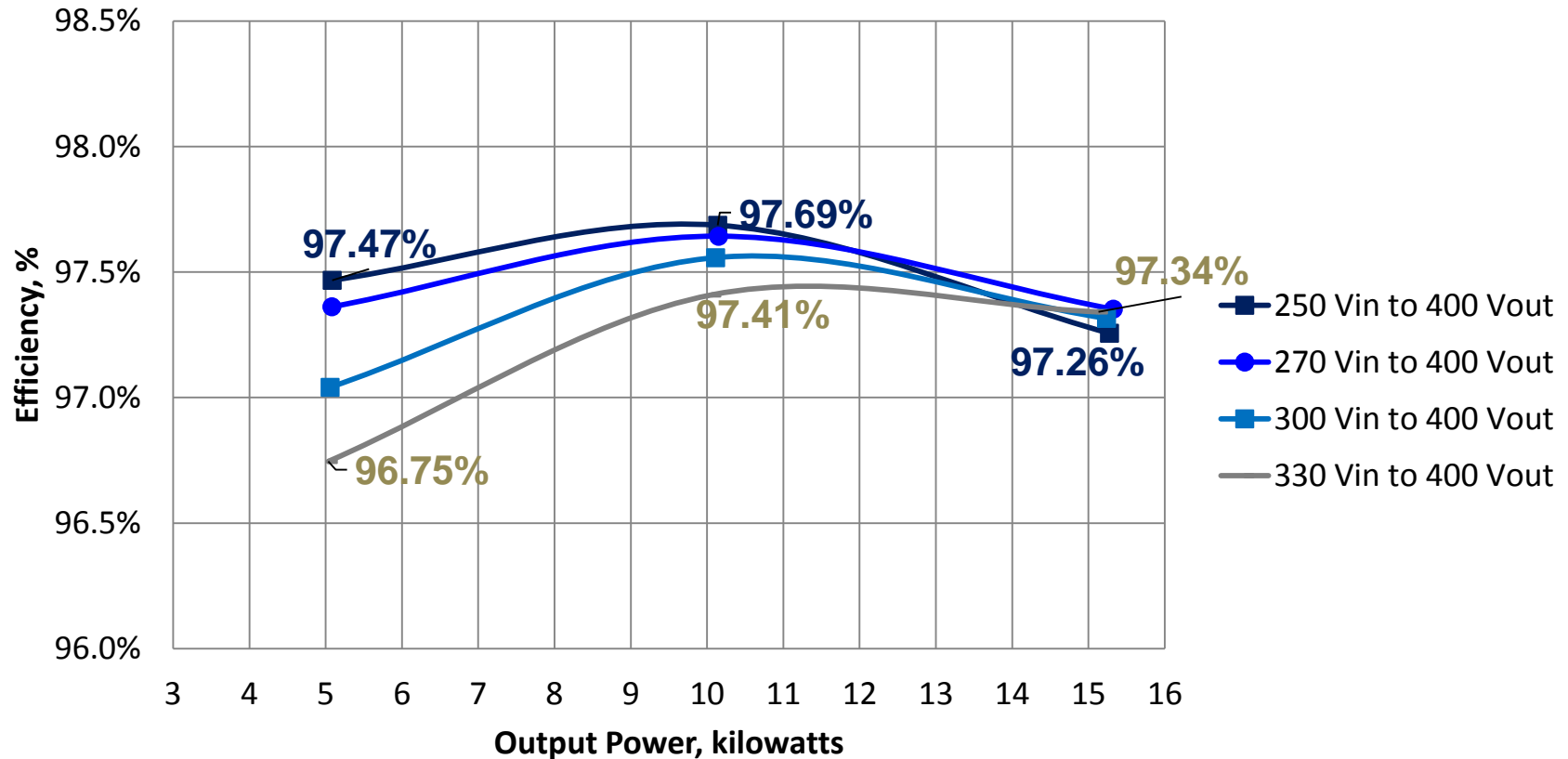


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# Performance Results

SiC PPU Overall Efficiency vs. Output Power: 400 Vout

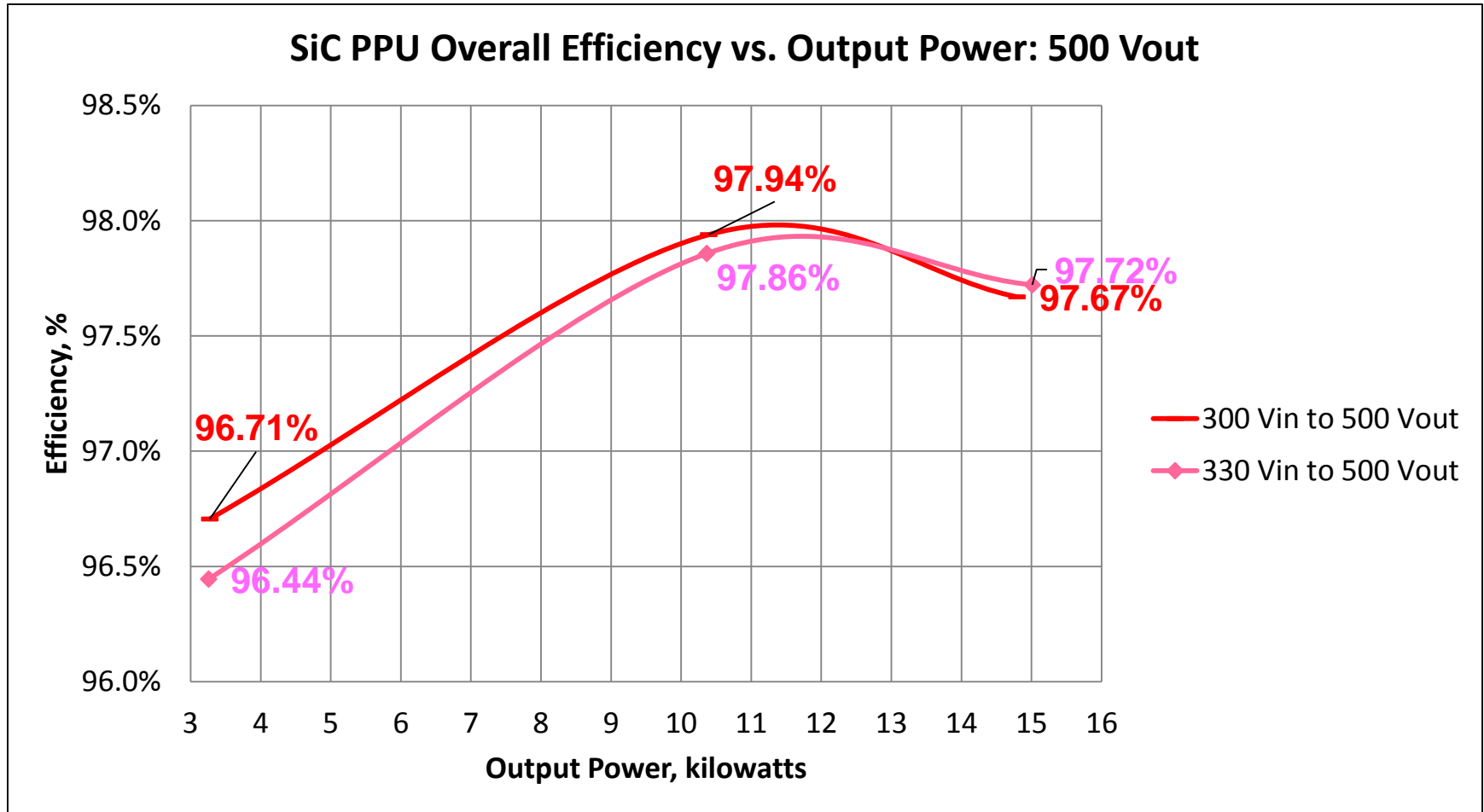


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# Performance Results



$$\text{Efficiency} = \frac{(\text{Discharge Output Power} + \sum \text{Auxiliary Output Power} + \text{Housekeeping Power})}{(\text{Low Voltage Power Input} + \text{High Voltage Power Input})}$$



# Performance Results

	Test Conditions (full-scale value)	Line Regulation, %	Load Regulation, %	Ripple, %
<b>Discharge Supply</b>	V <sub>out</sub> = 400 VDC (400 VDC)	2.90%	0.74%	1.25%
<b>Inner Magnet Supply</b>	I <sub>out</sub> = 5 ADC (10 ADC)	0.08%	0.08%	0.08%
<b>Outer Magnet Supply</b>	I <sub>out</sub> = 5 ADC (10 ADC)	0.03%	0.02%	0.20%
<b>Heater Supply</b>	I <sub>out</sub> = 5 ADC (9 ADC)	0.08%	0.04%	0.20%
<b>Keeper Supply</b>	I <sub>out</sub> = 2 ADC (3 ADC)	0.01%	0.02%	0.80%

EQUATION	VARIATION
$\text{Line Regulation} = \frac{\Delta \text{Regulated Output}}{\Delta \text{Input Voltage}}$	<p>For discharge supply, high voltage input varied from 250 – 330 VDC</p> <p>For auxiliary supplies, low voltage input varied from 23 - 36 VDC</p>
$\text{Load Regulation} = \frac{\Delta \text{Regulated Output}}{\text{Nominal Regulated Output Value}}$	<p>For each supply, load resistance was varied from 30% to 100% of the full load capability of the supply.</p>



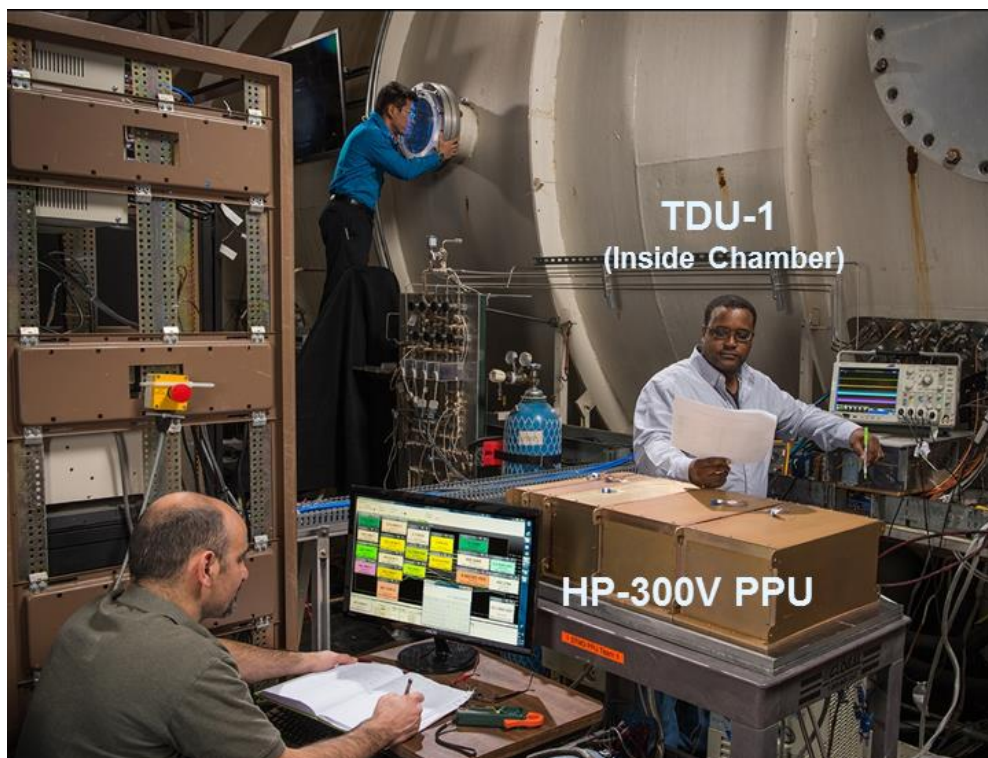
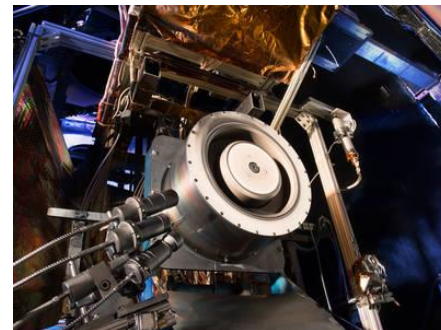
# Performance Results

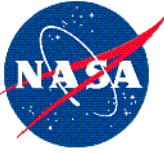
Brassboard SiC PPU Thermal Result Summary High Voltage Input: 300 VDC Low Voltage Input: 28 VDC Discharge Output Voltage Setting: 400 VDC, Discharge Output Power: 15 kW					
Component Temperature	Ambient Steady State Temperature, C <i>Baseplate at 25 C</i>	Vacuum Steady State Temperature, C <i>Baseplate at 25 C</i>	Vacuum Steady State Temperature, C <i>Baseplate at 50 C</i>	Vacuum Steady State Temperature, C <i>Baseplate at 5 C</i>	$\Delta T$ (Vacuum-Ambient) <i>Baseplate at 25 C</i>
Discharge Module 2, Inside Transformer Windings	54.6	67.3	97.2	61.4	12.7
High Voltage Bus Input Filter Differential Inductor	47.6	66.2	81.5	51.5	18.6
Housekeeping Power Supply, DC-DC Converter	38.8	53.8	73.2	36.5	15.1
Discharge Module 2 Transformer Case	45.9	52.5	74.8	35.2	6.6
Discharge Module 2 SiC MOSFET	33.3	35.3	58.8	16.3	2.0
Low Voltage Bus Total Input Current Sensor	33.1	45.6	64.8	27.7	12.4
Discharge Module 2 Gate Drive Board	35.9	42.2	64.3	24.3	6.4
Discharge Module 2 SiC Output Rectifier Diode	38.7	40.6	64.1	21.5	1.9
Discharge Module 2 Baseplate Temperature	25.6	26.7	50.1	6.9	1.1



# Performance Results

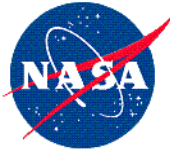
- Integrated Thruster Demonstration





# Forward Work

- NASA's Glenn Research Center with support from the Goddard Space Flight Center has investigated the ability of commercially available SiC devices to survive the space radiation environment.
  - ***To date, none of the SiC components under test have passed all of the required space environment radiation tests.***
- On-going research seeks to better understand and analyze the failure modes of SiC power devices in order to develop space-qualified devices for future NASA missions.



# Conclusion

- SiC components and high voltage design contributed to the superior performance demonstrated by the 15 kW brassboard SiC PPU under ambient and vacuum conditions.
  - Peak PPU overall efficiencies in excess of 97% at full-power in ambient test environment
  - All component temperatures within 30C of baseplate in ambient test environment
  - Vacuum performance results consistent with ambient performance results
  - Integrated test demonstrated compatibility with a technology demonstration unit Hall Effect Thruster
- Future work is necessary to demonstrate that SiC power devices can withstand the space radiation environment.





# Acknowledgements

- **Co-Authors:** Luis Pinero, Robert Scheidegger, Michael Aulisio, Marcelo Gonzalez, and Arthur Birchenough
- **Engineers, Designers, and Technicians** at NASA Glenn Research Center who contributed to the success of these development efforts.